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FEB 75 E BENKO, H C BOWERS, W R LANE DAAB05-73-C-2070

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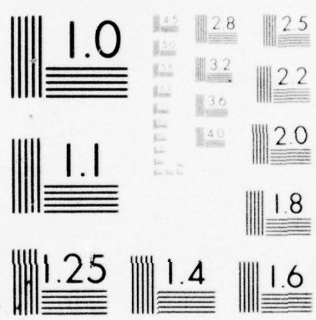

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SEVENTH QUARTERLY PROGRESS REPORT

PRODUCTION ENGINEERING MEASURES

SOLID STATE MICROWAVE OSCILLATORS FOR FUZES

CONTRACT NO. DAAB05-73-C-2070

1 NOVEMBER 1974 TO 1 FEBRUARY 1975

Prepared for

UNITED STATES ARMY ELECTRONICS COMMAND

PHILADELPHIA, PENNSYLVANIA 19103

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PRODUCTION ENGINEERING MEASURES SOLID STATE MICROWAVE OSCILLATORS FOR FUZES.

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Report No. W-40376-7

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SEVENTH QUARTERLY PROGRESS REPORT, no. 7,

1 NOV[redacted] [redacted]74 ~~to~~ 1 FEB[redacted] [redacted]75

OBJECT OF PROGRAM

The objective of the work performed under this contract is to establish a production capability for narrow pulse TRAPATT oscillators to operate at 500 MHz and 4 GHz.

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CONTRACT NO. DAAB05-73-C-2070

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FOREWORD

This project was initiated by the U.S. Army Electronics Command. The work described herein was carried out at the Hughes Aircraft Company, 3100 West Lomita Boulevard, Torrance, California 90509. This report summarizes the development program carried out during the period covering 1 November 1974 through 1 February 1975.

ABSTRACT

Work performed during the seventh quarter toward establishing a manufacturing capability for TRAPATT oscillators at 800 MHz and 4 GHz is described in this document. Continued efforts to optimize the deeply diffused TRAPATT diode are reported. Over 800 watts peak power at 0.84 GHz was achieved from a single diode at 34 percent efficiency. A miniature microstrip circuit for operation near 0.8 GHz is reported. An analysis is given which compares the fundamental and second harmonic extraction modes of TRAPATT oscillators.

1.0 INTRODUCTION AND SUMMARY

The objective of work performed under this contract is to establish a production capability for narrow pulse TRAPATT oscillators to operate at 800 MHz and 4 GHz. Diodes, oscillator circuitry, and bias modulators are all to be investigated.

Diode fabrication was continued in an effort to optimize the deeply diffused TRAPATT diode structure. Consistently improving performance leading to an advancement of the state-of-the-art was observed during the quarter. Using a single packaged diode over 800 watts of peak RF power with 34 percent efficiency was obtained at a frequency of 0.84 GHz.

Substantial progress was made on the design and development of a micro-strip UHF oscillator. This circuit occupies a volume approximately one-tenth that of the previously reported discrete element circuit. The new circuit also has superior heat sinking properties and is much more rugged in comparison to the previous circuit.

An investigation of the relative attributes of fundamental and second harmonic extraction is reported. Results are presented which suggest that for a circuit capable of matching to some minimum magnitude of large signal diode impedance, more power can be obtained at frequencies above 3 GHz using second harmonic extraction as compared to fundamental extraction.

2.0 DIODE FABRICATION

2.1 SUMMARY

Diode fabrication continued in an effort to optimize TRAPATT performance at 0.5 and 4 GHz and to provide diodes for circuit development and testing at these frequencies. The optimization was primarily a matter of finding the correct design and process parameters for performance at the two frequencies. As in the past, performance of both types of diodes was generally good with much improved yields. Over 800 watts has been obtained in the UHF region with efficiencies greater than 30 percent. At lower power levels, efficiencies approaching 40 percent have been obtained. Consistent performance of 40 to more than 50 watts has been obtained in S-band using diodes operating in the second harmonic extraction mode. Because second harmonic extraction is being used, the efficiencies in general are lower, typically in the 15 to 20 percent range. A few diodes, however, have exhibited higher efficiencies than this.

Twenty-five lots of UHF diodes and fourteen lots of S-band diodes were processed and tested in the past quarter. More than 60 percent of the UHF diode lots yielded powers in excess of 200 watts. In S-band approximately 65 percent of the lots yielded powers in excess of 40 watts in the 3 to 4 GHz range.

The epi material for the lots processed in the past quarter used silane and dichlorosilane. All of the diffusions were of the deep type as described in the previous quarterly report. Processing of these diodes for the most part followed standard procedures as previously described with all devices processed using the pill technology discussed in earlier reports.

2.2 EPITAXIAL GROWTH

A total of eleven 6-wafer epitaxial lots were processed for TRAPATT diode fabrication. Seven of these were targeted for UHF devices and four lots were targeted for S-band harmonic extraction devices. Both silane and dichlorosilane was used for this epi material.

During December the modifications to the horizontal epitaxial reactor gas control system were completed. In addition to allowing epi growth from dichlorosilane, the new system has provisions for n and p doping with mass flow controls replacing flow meters at all critical metering and control points. After initial calibration, epitaxial growth of material for UHF diodes began late in December. Initial evaluation of the material was encouraging.

The high yields exhibited in this quarter indicate that the quality of the epitaxial material we are presently growing is quite adequate for good TRAPATT devices.

2.3 DIFFUSION

All of the wafers processed for testing in the past quarter utilized the deep diffusion method described in the previous quarterly report. There is no doubt that the change to this method has immensely improved the yield of diodes. Less than 10 percent of the lots fabricated by this method exhibit burn-out problems and virtually all of those lots which have been tested exhibit good switching characteristics. As noted above, the yield of lots which produce reasonable powers is greater than 60%. This represents a substantial improvement over other types of processing which have been used for TRAPATT diodes.

2.4 PERFORMANCE SUMMARY

A summary of single diode performance for the UHF diode lots tested this past quarter is given in Table 1. Only those lots which yielded more than 200 watts of power are shown in the table. These 15 lots resulted from processing and testing a total of 25 lots. The data shown in this table in general represents the best result obtained for the given lot, but in general typical results are only slightly less than those shown in the table. Although the criteria for diodes in this table was power output greater than 200 watts, it can be seen that many performed considerably better than this. Several lots yielded powers in excess of 400 watts and one lot, MWA 778, yielded over 800 watts of power at 0.84 GHz with an efficiency of 34 percent. It should be noted that although these diodes represent a substantial variation in depletion layer width and breakdown voltage, performance was limited to the 0.63-1 GHz range. Good performance at precisely 0.5 GHz still has not been achieved.

A summary of diode performance in S-band is given in Table 2. Here nine lots exhibited a power output of greater than 40 watts in the 3 to 4 GHz range. This is a result of processing and testing a total of 14 lots in this frequency range. This represents a yield of approximately 64 percent. It is apparent from the table that not all of the lots are optimized for performance at 4 GHz, and we are continuing to tighten controls on the diode fabrication in order to achieve this optimization. It can also be seen from the table that the efficiencies achieved in S-band are not as great as those achieved with the UHF diodes shown in Table 1. This is because we are utilizing second harmonic extraction to obtain these results. This is being done because it is felt that second harmonic extraction will yield greater powers at 4 GHz than would fundamental extraction and that it is necessary to pay some penalty in efficiency to achieve such results.

TABLE 1

UHF SINGLE DIODE PERFORMANCE

DIODE LOT #	DIAM. (MIL)	CURRENT (AMPS)	POWER (WATTS)	FREQ (GHz)	EFFICIENCY (%)
MWA 762	33	12	450	.65	38
MWA 771	32	17	510	.93	24
MWA 772	32	7.4	220	.75	19
MWA 773	32	12	480	.72	39
MWA 777	32	12	754	.65	39
MWA 778	33	16	826	.84	34
MWA 782	33	10	322	.86	22
MWA 783	33	15	616	.90	30
MWA 788	32	9	355	.66	33
MWA 789	32	9	288	.66	23
MWA 793	32	10	346	.6	27
MWA 794	26	7.5	421	.62	35
MWA 799	32	8	374	.63	24
MWA 800	27	6	270	.63	32
MWA 801	32	15	419	1.0	20

TABLE 2

S-BAND DIODE PERFORMANCE

DIODE LOT #	DIAM. (MIL)	POWER (WATTS)	FREQ (GHz)	EFFICIENCY (%)
MWA 754	8	54	3	40
MWA 769	12	41	3.3	7
MWA 770	12	66	3.6	18
MWA 775	10	71	3.2	13
MWA 775	10	61	4.0	14
MWA 776	11	55	4.0	14
MWA 779	9	45	3.3	16
MWA 780	11	57	3.1	25
MWA 780	11	47	4.3	18
MWA 785	11	65	3.1	14
MWA 786	11	67	3.3	19
MWA 786	11	40	4.3	12

2.5 DIODE DESIGN

We are continuing to use the previously described deep diffusion technique for fabricating TRAPATT diodes. The resulting field profiles resulting from this technique were described in detail in the previous quarterly report. Of primary importance is the result that a significant portion of the electric field exists both on the p-side and n-side of the junction. Thus, we obtain a double sided or double drift type diode. It is not yet clear what parameters in the design and fabrication of these diodes are the most important. Some of the parameters that can be considered are depletion layer width, the ratio of depletion width on the p-side of the junction to that on the n-side of the junction, X_p/X_n, and details in the field profile near the edges of the depletion layer region. Since these parameters are inter-related, it is proving difficult to analyze and determine which of these are the most significant. So far it has been found that a wide range of depletion layer widths, breakdown voltages, and X_p/X_n ratios yield good performance in the 0.63-1 GHz range. We are continuing to monitor these parameters and to vary them in a controlled fashion in an effort to determine which combination of parameters is optimum.

As noted above, we still have not achieved satisfactory performance at precisely 0.5 GHz. The exact reason for this is not yet understood, but it is felt that because of the double-sided structure that we are using perhaps a greater depletion layer width and, hence, breakdown voltage are required for performance at this frequency. Efforts to design and make such diodes will occur in the next few reporting periods.

3.0 RF CIRCUITS

3.1 UHF OSCILLATOR CIRCUIT DEVELOPMENT

The variation of detected RF pulse leading-edge jitter over the oscillation frequency tuning range at a constant current level was studied using the optimized 1.8" x 1.8" x 0.7" box circuit and our MWA 729 diodes. For a current level of 10A, the circuit was tuned for maximum power consistent with optimum efficiency. This tuning criteria yields minimum RF leading-edge jitter, otpimum voltage collapse ratio (i.e. optimum $V_{operating}/V_{breakdown}$) and high quality output waveforms for a fixed bias current. Figure 1 shows typical operational output waveforms for the above tuning condition. Note that the waveforms exhibit little or no jitter. By retuning the circuit, the oscillation frequency was varied at the same fixed bias current. The results obtained are shown in Figure 2 where the jitter is plotted as a function of the ratio of operating frequency to optimum frequency. At the minimum jitter level (0.08 ns) the measured oscillator performance was 386 watts peak power, 38 percent efficiency and 0.78 GHz oscillation frequency. At the maximum jitter (5.5 ns) the measured performance was 525 watts peak power, 22 percent efficiency and 0.74 GHz oscillation frequency, but in this case the quality of the output waveforms was reduced. The results obtained suggest that for optimum lumped-element TRAPATT oscillator performance at a given bias current, the oscillator circuit should not be tuned for maximum RF output power.

During this quarter much progress was made on the design and development of a new planar oscillator circuit using microwave integrated circuit (MIC) techniques. The resultant circuit had a volume of 0.20 in^3 compared to 2.2 in^3 for the box circuit. The RF circuit coils were obtained by etching patterns in the metallization on a Duroid substrate. Good thermal stability and component isolation was achieved by using small negative temperature coefficient capacitors. The new circuit has yielded excellent

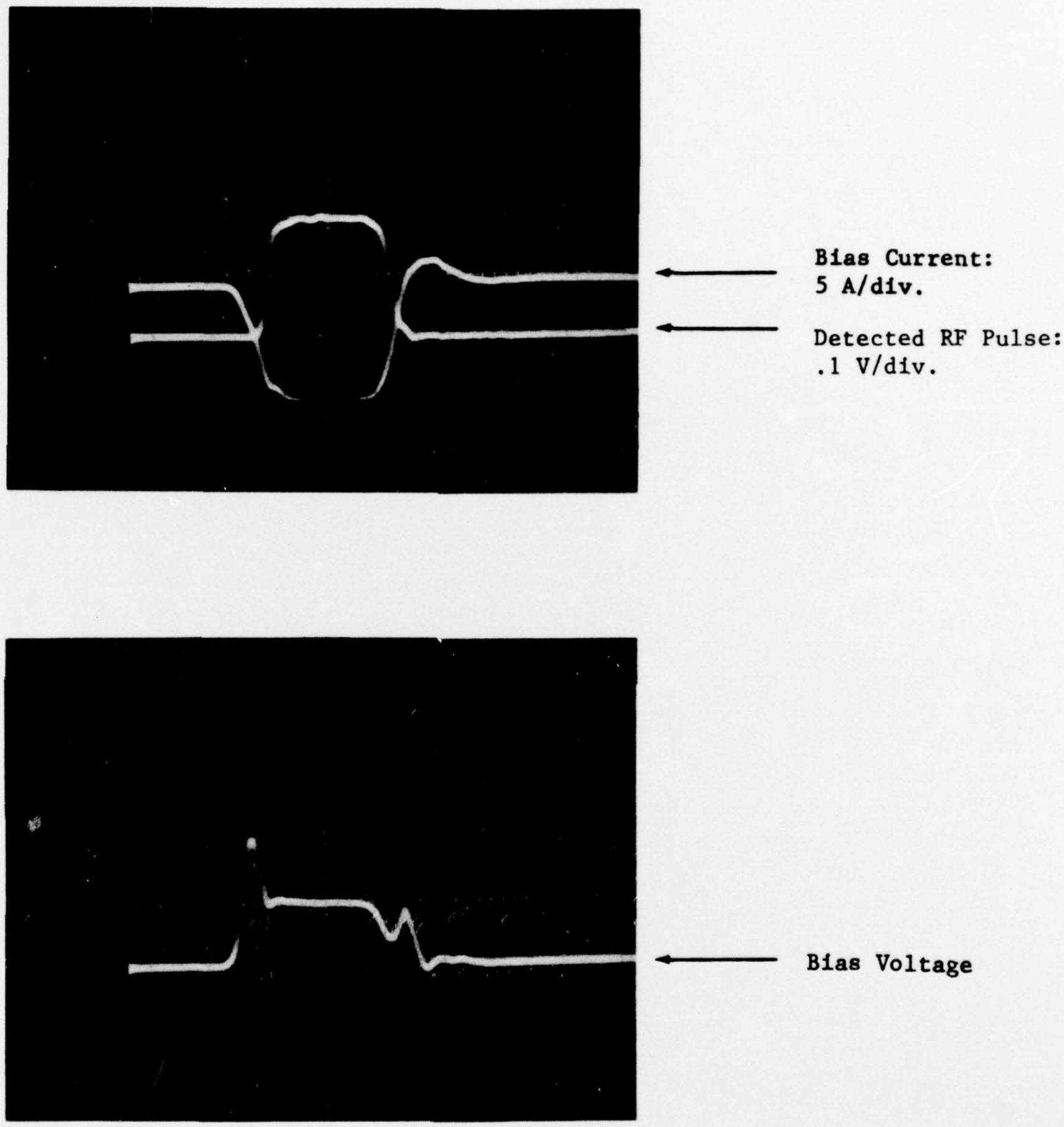

Figure 1 Typical operational output waveforms for optimally tuned lumped-element TRAPATT oscillator. (Diode MWA 729, RF power = 386 watts, f_o = 0.78 GHz.)

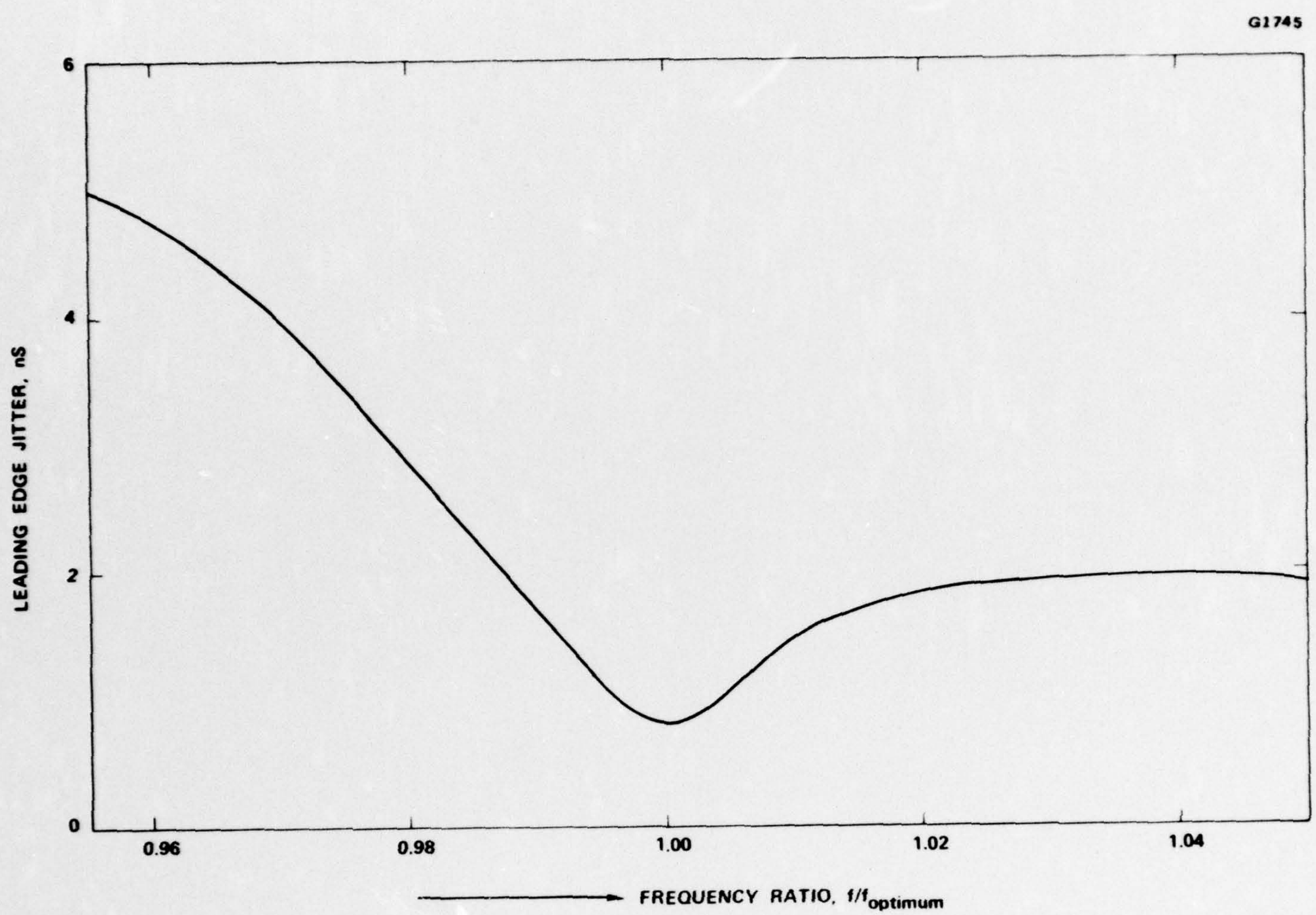

Figure 2 Detected RF leading edge jitter versus frequency ratio, $f/f_{optimum}$; diode MWA 729. I_{bias} = 10 A.

performance with its power capability comparable to that of the optimized 1.8" x 1.8" x 0.7" box circuit.

The detuning effects of materials in proximity to the planar microwave integrated circuit were investigated. Enclosing the circuit in an aluminum housing caused a slight detuning which could easily be eliminated by retuning the circuit. Similarly, it was found that any radiation effects associated with the planar circuit may be greatly reduced by optimal tuning and by providing a covering lid for the housed circuit.

3.2 4 GHz CIRCUIT DEVELOPMENT

Two of the modes commonly used in high peak power TRAPATT oscillators are compared here. These modes are distinguished by the number of the harmonic at which power is extracted. In a TRAPATT oscillator which has been adjusted to eliminate subharmonic oscillations the current and voltage waveforms at the diode chip have significant Fourier components at some minimum frequency, f_o, designated the fundamental frequency, and at many integer multiples of that frequency. With fundamental power extraction the oscillator is adjusted to enhance power transfer from the diode to output load at frequency f_o. With second harmonic extraction the waveforms are adjusted to reduce power transfer at f_o and maximize power output at frequency $2f_o$. The purpose of this section is to compare the output powers obtainable from these two modes of TRAPATT oscillation. This investigation is based primarily on the direct observation of many TRAPATT oscillators operating in these modes. Only minimal recourse is made to mathematical models of either the diode or assiciated circuitry because of the difficulty in establishing the parameters and accuracy of many such models.

Laboratory test data of diodes manufactured from approximately 100 different wafers was collector for this investigation. Since the characteristics of nearly optimum TRAPATT operation are of interest here, only

results corresponding to nearly state-of-the-art combinations of power and efficiency were included for use in this study. All diodes utilized an n-type epitaxial layer grown upon an n^+ substrate with either arsenic or antimony dopant. A deep boron diffusion was made into the epitaxial layer to produce a highly graded junction. The resulting depletion layer tended to be equally divided between n and p type regions. The diode areas ranged from 7 to 32 mils. When operated in the fundamental extraction mode, peak output powers between 50 and 1000 watts were achieved at frequencies between 0.5 and 5.0 GHz. At frequencies below 1 GHz the circuit used either discrete, lumped elements[1] or distributed elements on microstrip whose length was small relative to a wavelength at the fundamental frequency.

Our experience with diodes operating in the fundamental extraction mode will be summarized first. Figure 3 shows the depletion layerwidth, W, and fundamental output frequency for the diodes. The data indicates that these quantities are approximately related by

$$W = \frac{7}{f_o} \tag{1}$$

where W and f_o have units of microns and GHz, respectively. In Figure 4 the current density and breakdown voltage of these same diodes is given. A linear approximation to these quantities is

$$J = (17 - .07\, V_B) \times 10^3 \text{ A/cm}^2 \tag{2}$$

where V_B is the breakdown voltage.

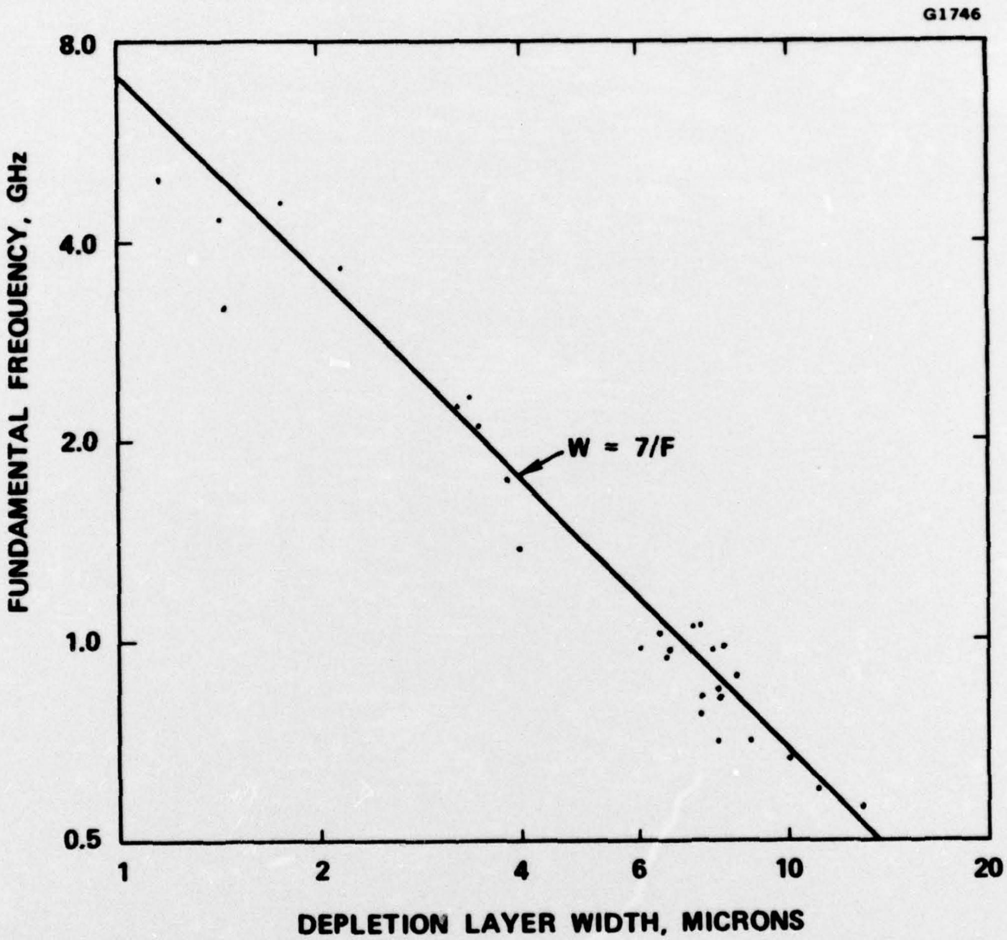

Figure 3 Fundamental frequency versus depletion layer width.

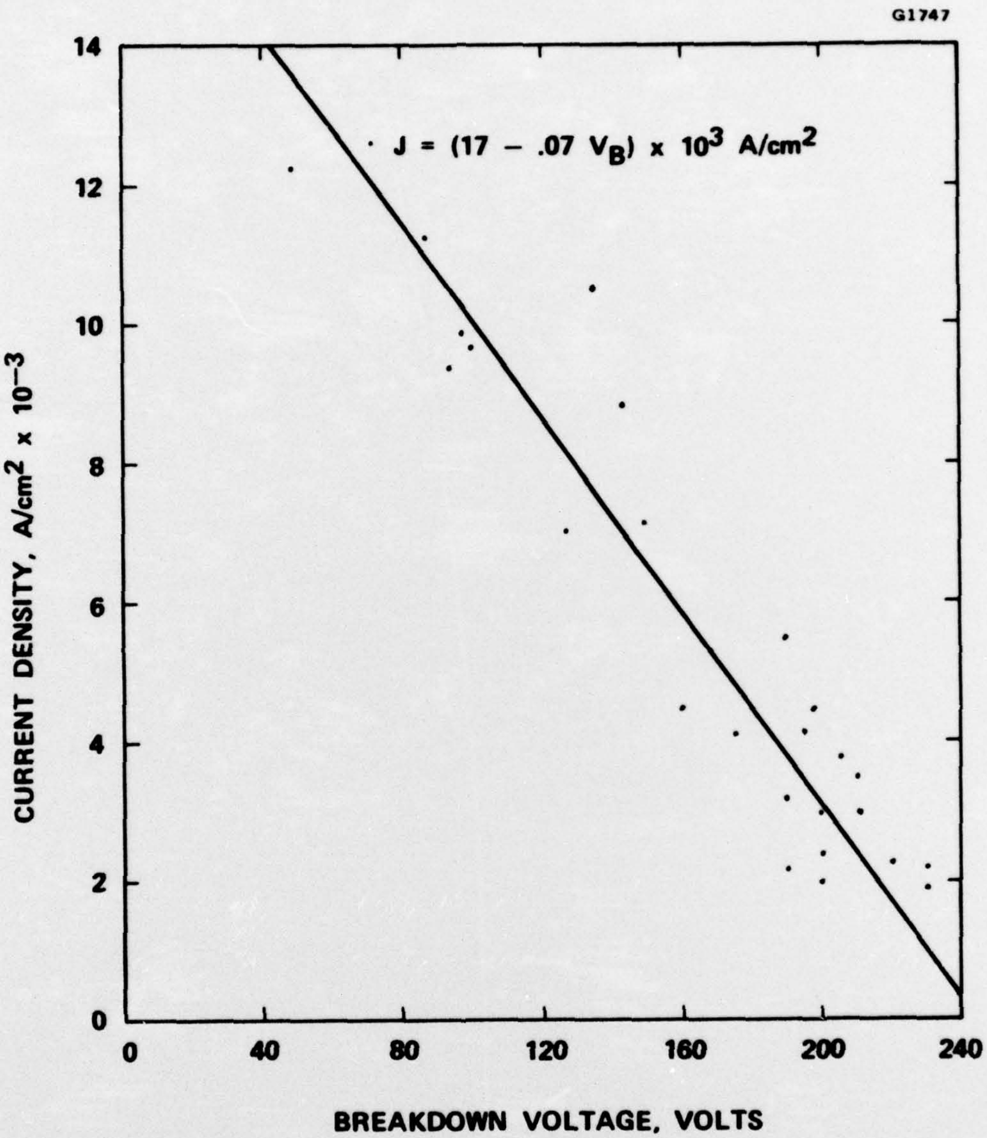

Figure 4 Current density versus breakdown voltage.

For the diodes considered here it was observed that the operating voltage normalized to the breakdown voltage, K_o, and the DC to RF conversion efficiency, η, was nearly constant for fundamental output frequencies between 0.5 and 5.0 GHz. Also, for these highly punched-through diodes the breakdown voltage is approximately proportional to $W^{.76}$ for frequencies of interest here. From this generalization and (3), it follows that

$$V_B \approx K_v f_o^{-.76}$$

where $K_v \approx 154\text{V GHz}^{.76}$. The normalized output power, P_N, for a unit of diode area is given by $K_o V_B J$ which, from (2), can be written as:

$$P_N = \eta K_o V_B (17 - .07 V_B) \times 10^3 \text{ watts/cm}^2. \qquad (4)$$

Upon substituting (3) into (4) and using $\eta \approx .32$ and $K_o \approx .67$, P_N can be expressed as a function of fundamental frequency and plotted as shown in Figure 5. It is significant that P_N decreases for values of $f_o > 1.5$ GHz.

The output power obtainable from a TRAPATT diode is limited by the value of P_N indicated in Figure 5 and the maximum diode area and associated minimum impedance levels that can be accommodated by the oscillator circuit. The impedances of interest are, of course, large signal impedances. However, it can be shown from simplified models[2] of the TRAPATT mode that the magnitude of large signal impedances scale approximately as the small signal reactance associated with the depletion layer capacitance of the diode at or above the punch-through voltage. This relationship is quite useful in estimating the power frequency characteristics of TRAPATT diodes. The reactance of the depletion layer capacitance, C_D, is

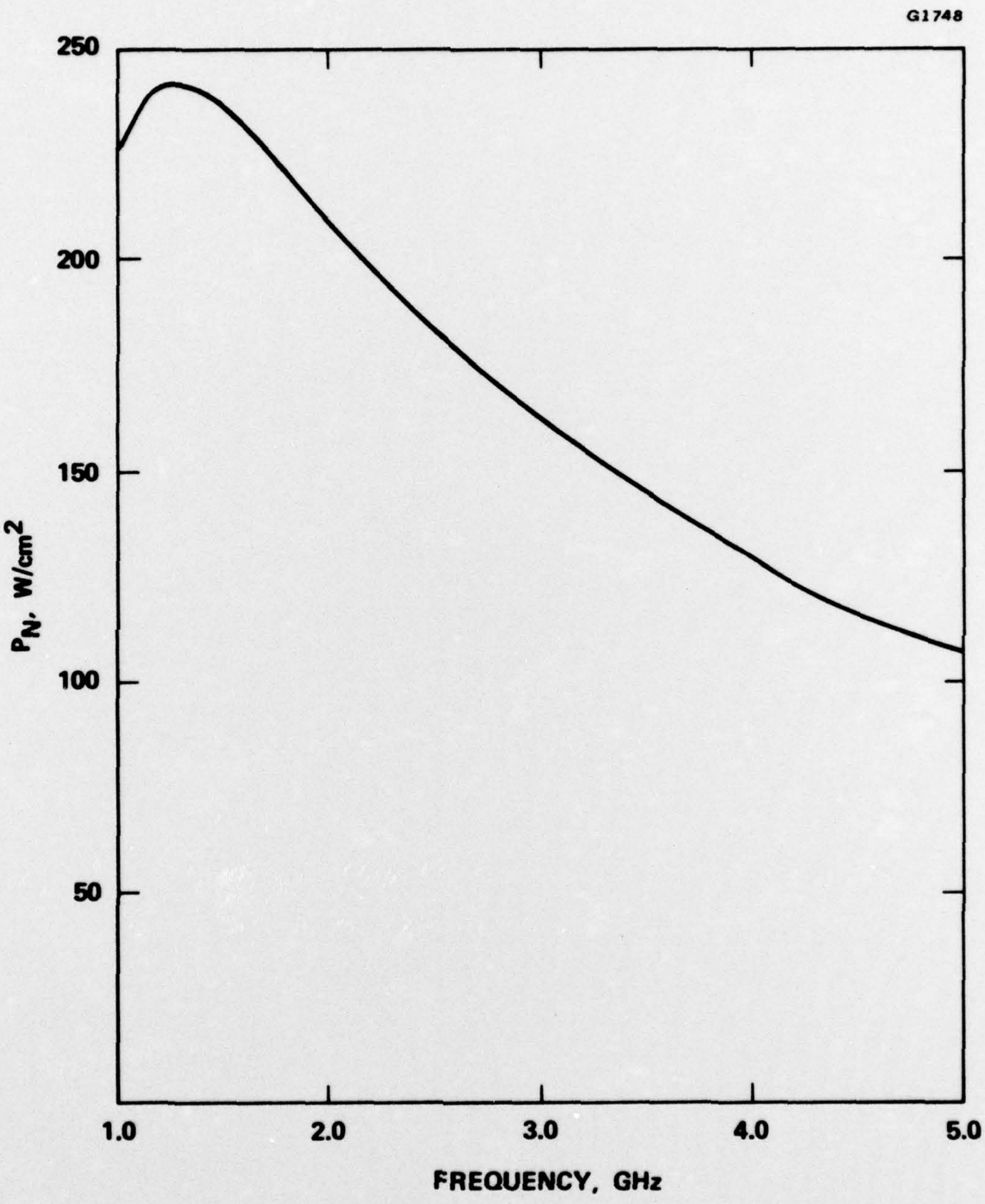

Figure 5 Output power density versus frequency.

proportional to W^{-1} and using (1) it follows that the reactance of the depletion layer capacitance X_N, per unit of diode area is proportional to f_o^{-2}. From Figure 5 it follows then that the product $P_N X_N$ and, therefore, the output power obtainable subject to some lower bound on realizable impedances, decreases somewhat faster than f_o^{-2} for $f_o > 1.5$ GHz.

Having delineated some characteristics of TRAPATT diodes with fundamental extraction, a comparison with the characteristics of second harmonic extraction will now be made. It has been observed here and by others[3] that the efficiency decreases by a factor of approximately two when changing from fundamental to second harmonic extraction with the fundamental frequency remaining constant and the output frequency doubling. However, for optimum tuning the bias current density and operating voltage are approximately the same for these two modes. Therefore, from (4) the normalized output power density is decreased by a factor of 2 when power is extracted at the second harmonic. An alternative means of doubling the output frequency is to use fundamental extraction at twice the original fundamental frequency. Since the power impedance product falls off as f^{-2} as discussed above, the latter approach will decrease the output power by at least a factor of four if the original fundamental frequency was greater than 1.5 GHz. It would appear, then, that for output frequencies greater than 3 GHz, more power at reduced efficiency can be obtained using second harmonic extraction providing the large signal impedances associated with second harmonic extraction are comparable to those with fundamental extraction.

Measurements were made to compare the large signal impedances of the fundamental and second harmonic modes. The circuit used in these measurements is the standard coaxial test circuit which has been described in previous reports. This circuit, illustrated in Figure 6 has an impedance matching transformer near the diode followed by a 50 ohm line somewhat less than one-half wavelength long which is, in turn, followed by tuning

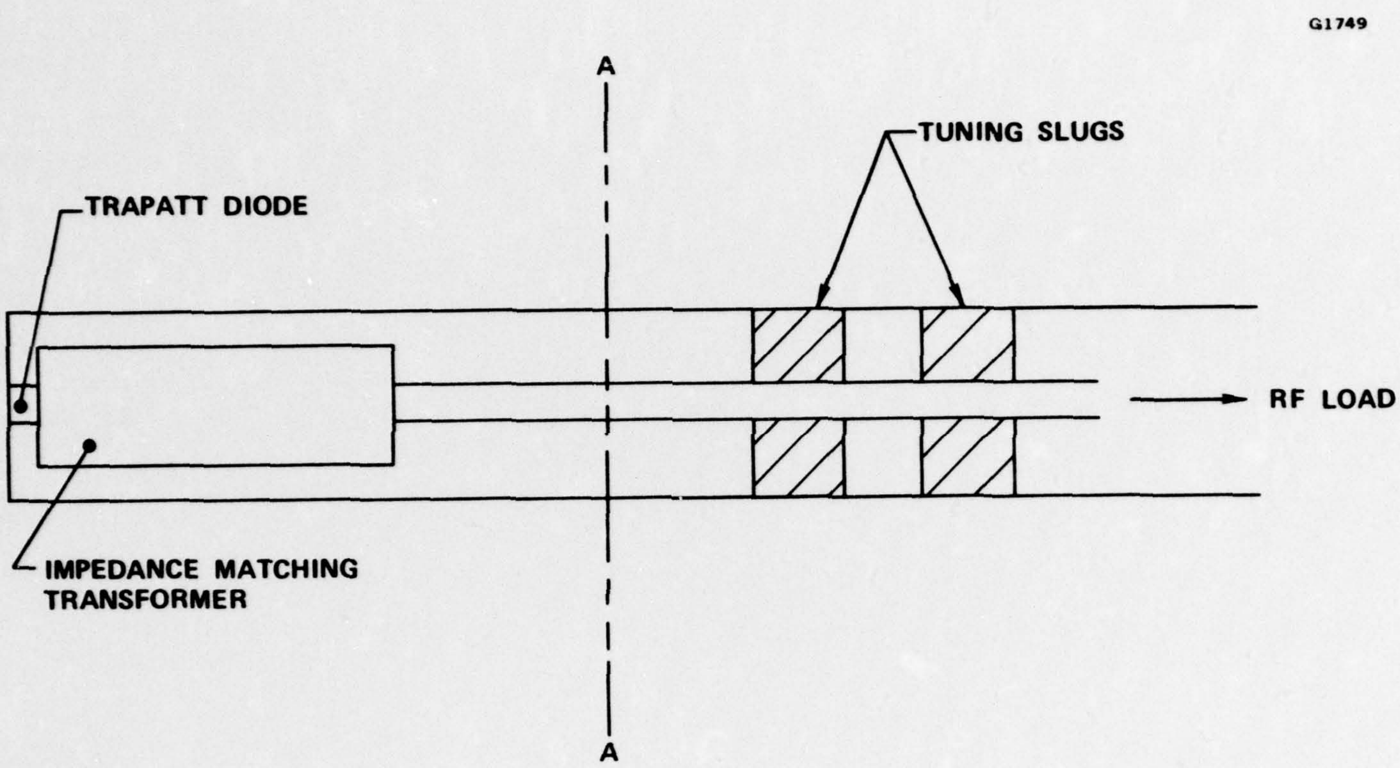

Figure 6 Coaxial oscillator circuit used for large-signal impedance measurements.

slugs and the output load. All elements between plane A-A and the diode are linear, reciprocal elements which can be modeled as a two-port network. This network at any particular frequency can be fully characterized by a matrix of four z parameters. The tuning slugs and output load constitute the load at, say, port 2 of the network and the TRAPATT diode chip is situated at port 1. All parasitic impedances associated with the diode package and mount are considered part of this network. The location of plane A-A is chosen so the fields at that plane are TEM. Therefore, the impedance of the slugs and output load as measured with a network analyzer inserted at plane A-A will be the same as the impedance at that plane with the diode and associated matching transformer in place. The impedance so measured is regarded as an impedance Z_2 at port 2 of the two-port network. The diode impedance Z_D is then given by $Z_D = z_{11} - z_{12}z_{21}/(z_{22} + z_2)$ where the z_{ij} are the impedance parameters of the two port network.

The z_{ij} are determined by replacing the tuning slugs and output load with a computer-controlled automatic network analyzer and measuring the impedance into port 2 with the TRAPATT diode replaced by loads of known impedance. Since the two-port network contains only reciprocal elements, $z_{12} = z_{21}$, and three impedance measurements with different reference loads are necessary to specify the z_{ij}. The reference loads used consisted of known impedances contained in packages essentially identical to that of the TRAPATT diodes. One reference impedance, denoted as Z_{r1}, had a value of infinity and was realized by removing a TRAPATT diode chip from the package without changing the position of the bonding strap. A second reference impedance, $Z_{r2} = 0$, was constructed by bonding the package straps to the surface where the actual diode chip would otherwise be bonded. A third impedance, $Z_{r3} = (jWC_r)^{-1}$, was realized by replacing the diode chip with a chip capacitor of known capacitance Cr. The z parameters of the network were then evaluated using

$$z_{11} = z_{m1}$$

$$z_{22} = \frac{z_{m3} + z_{11}}{jWC_r(z_{m3} - z_{m2})}$$

$$z_{12} = z_{21} = (z_{11} - z_{m2})z_{22}$$

where z_{m1}, z_{m2}, and z_{m3} are the impedances measured at plane A-A when the diode is replaced by reference loads z_{r1}, z_{r2}, and z_{r3}, respectively.

This technique does not require making any assumptions about the values of parasitic impedances surrounding the diode. The accuracy of this technique was evaluated by replacing the TRAPATT diode with a voltage controlled capacitance, inferring this capacitance from the measurements described above, and comparing these capacitance values with those obtained using a small test signal at 1 MHz. Generally, at a given varactor bias voltage these capacitance values agreed within 10 percent over a frequency range of 2 to 8 GHz.

Typical values for large signal impedance of a C-band TRAPATT diode at the fundamental and second harmonic are shown in Table 3. These results are for an oscillator using the same diode but tuned in one case for fundamental extraction near 2 GHz and in the other case for second harmonic extraction at approximately twice that frequency. Since the impedance magnitudes with second harmonic extraction are generally as large as those for fundamental extraction, it appears that it should be possible to use as large a diode in the former case as in the latter with an oscillator circuit capable of matching to diode impedance magnitudes above some specified value.

In conclusion, the results of this study suggest that above 3 GHz oscillators using deeply diffused TRAPATT diodes can generate a higher peak power

using second harmonic extraction as compared to fundamental extraction. Such increased power is obtained, however, at the expense of reducing the efficiency by approximately a factor of two.

TABLE 3

Fundamental Frequency (GHz)	Output Harmonic Number	Output Power (W)	Efficiency Efficiency (%)	Fundamental Impedance (Ω)	Second Harmonic Impedance (Ω)
2.075	2	60	17	.46 + j3.7	19.4 + j17.4
2.082	1	134	31	5.0 + j3.4	2.3 - j1.4

4.0 CONCLUSION

During this quarter approximately 40 lots of diodes were processed and tested in an effort to optimize performance at 0.5 and 4 GHz. UHF diodes producing in excess of 250 watts at 0.8 GHz with 0.1 percent duty cycle can now be fabricated with a good yield. However, tests at 2 percent duty indicate a reduced reliability. Consequently, additional work is needed to reduce the thermal impedance of the bond between the diode chip and the heat sink.

The progress made with the UHF microstrip circuit is encouraging. The feasibility of producing a UHF oscillator in very small volume on microstrip has been demonstrated. Additional work is needed to improve the heat sinking of the diode in this circuit. Further efforts are also necessary to simultaneously achieve good electrical and mechanical contact with the anode of the diode.

The study conducted this quarter on the relative characteristics of fundamental and second harmonic extraction confirm that more power can be obtained at output frequencies above 3 GHz using second harmonic extraction. Such increased power is obtained, however, at the cost of reduced efficiency.

REFERENCES

1. C. O. G. Obah, E. Benko, T. A. Midford, H. C. BOwers and P. Y. Chao, "Single Diode 0.5 kW TRAPATT Oscillator," Elect. Letters, Vol. 10 No. 21, Oct. 17, 1974, pp. 430-431.

2. K. L. Kotzebne and R. D. Regier, "TRAPATT Diode Model for Circuit Design," Electronics Letters, Vol. 8, No. 8, April 1972, pp. 205-206.

3. C. P. Snapp, "Experiments concerning the nature of trapped-plasma mode harmonic extraction from p^+-n-n^+ avalanche diodes," IEEE Trans. Electron Devices, Vol. ED-19, Feb. 1972, pp. 172-181.